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HARD X-RAY EMISSION FROM ELLIPTICAL GALAXIES AND ITS CONTRIBUTION TO THE X-RAY BACKGROUND

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ABSTRACT

We explore the implications of the discovery of hard, power-law X-ray sources in the spectra of nearby elliptical galaxies for the origin of the X-ray background. The spectra of these sources are consistent with models of thermal bremsstrahlung emission from low radiative efficiency accretion flows around central supermassive black holes and are unique in that they approximately match that of the hard XRB. If such sources, with luminosities consistent with those observed in nearby ellipticals, are present in most early-type galaxies, then their integrated emission may contribute significantly to the XRB. These sources may also contribute to the hard source counts detected in deep X-ray surveys.

Subject headings: accretion, accretion disks — galaxies: nuclei – X-rays: general

1. INTRODUCTION

Although it is now clear that the Cosmic X-ray Background (XRB) results from the integrated X-ray emission from many discrete sources, and that a large fraction of the soft ($0.5-2$ keV) XRB is produced by Active Galactic Nuclei (AGN; e.g., Hasinger et al. 1998; Schmidt et al. 1998), the nature of the sources producing the energetically dominant, hard ($2-60$ keV) XRB remains largely unknown. Most current models for the XRB attempt to explain its origin within the context of AGN unification schemes and suggest that the XRB arises from the integrated emission of AGN with a range of intrinsic absorbing column densities (e.g., Setti & Woltjer 1989; Comastri et al. 1995 and references therein). A population of sources with hard X-ray spectra in the $2-10$ keV band have been discovered by ASCA and Beppo-SAX (Boyle et al. 1998; Ueda et al. 1998; Giommi et al. 1998), with a fraction of these sources showing evidence for heavy obscuration (Fiore et al. 1999). However, it remains unclear whether obscured AGN can fully account for the hard XRB. The most recent synthesis models, which include the latest constraints on the luminosity function and evolution of AGN (Miyaji, Hasinger & Schmidt 1999), cannot easily reproduce the hard counts observed in the ASCA (2-10 keV) and BeppoSAX (5-10 keV) bands and require a number ratio of type-2/type-1 AGN much higher than the locally observed value (Gilli, Risaliti & Salvati 1999).

The discrepancies within the context of AGN synthesis models for the XRB suggest the need for an additional population of hard-spectrum sources. In this *Letter*, we explore the implications of the discovery of hard, power-law X-ray components in the ASCA spectra of six nearby, giant elliptical galaxies (Allen, Di Matteo & Fabian 1999; hereafter ADF99). If most early-type galaxies contain a hard, power-law source with a luminosity of $\sim 10^{40}-10^{42}\,\mathrm{erg\,s^{-1}}$, as may be extrapolated from the detections of such components in both active (e.g. M87) and quiescent galaxies, then the integrated emission from these sources, distributed over a larger redshift interval, can make a significant contribution to the hard XRB.

Dynamical studies of elliptical galaxies indicate the presence of supermassive black holes in their nuclei, with masses in the range $10^8-10^{10}\,\mathrm{M_\odot}$ (e.g., Magorrian et al. 1998). As discussed by ADF99 and Di Matteo et al. (1999a; hereafter DM99), the hard X-ray components detected in nearby giant ellipticals are likely to be due, at least in part, to accretion onto their central black holes. In the cores of elliptical galaxies, accretion from the hot interstellar medium may proceed directly into a hot, low radiative efficiency regime (e.g., Fabian & Rees 1995). DM99 show that the hard X-ray components observed in these systems are consistent with models of thermal bremsstrahlung emission from hot, radiatively-inefficient accretion flows, with temperatures of $50-100$ keV. Given that the XRB spectrum in the $3-60$ keV band is also well described by a bremsstrahlung spectrum with $kT\sim 40$ keV, the hard X-ray sources in elliptical galaxies represent a unique class of object with emission spectra that closely match that of the XRB (see also Di Matteo & Fabian 1997).

2. HARD X-RAY EMISSION FROM ELLIPTICAL GALAXIES

2.1. *The observed power-law components*

ADF99 discuss ASCA observations of six nearby, giant elliptical galaxies: M87, NGC 4696 and NGC 1399 (the dominant galaxies of the Virgo, Centaurus and Fornax clusters) and three other giant ellipticals in the Virgo Cluster (NGC 4472, NGC 4636 and NGC 4649). All of these galaxies (with the exception of NGC 4696, which had not previously been studied in as much detail as the other systems) exhibit clear stellar and gas dynamical ev-

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idence for central, supermassive black holes in their nuclei, with masses in the range $10^8 - 10^{10}\,\mathrm{M}_\odot$ (e.g., Magorrian et al. 1998). The ASCA spectra for these systems reveal the presence of hard, power-law emission components, with energy indices $-0.5 < \alpha < 0.5$ (weighted-mean value $\alpha = 0.22$; a discussion detailing the reasons why the sources are unlikely to be heavily obscured AGN is given by ADF99) and intrinsic $1 - 10$ keV luminosities of $2 \times 10^{40} - 2 \times 10^{42}$ erg s^{-1}. These spectral slopes are harder and the luminosities are lower than typical values for Seyfert galaxies, identifying these objects as, potentially, a new class of X-ray source. The presence of hard components in all six galaxies studied also suggests that such sources may be ubiquitous in early-type galaxies.

2.2. *An empirical comparison*

We first compare the spectra of the power-law sources observed in nearby ellipticals with the $1 - 10$ keV XRB. ASCA and BeppoSAX observations of the cosmic XRB in the $1 - 7$ keV band can be well-described by a simple power-law model with an energy index, $\alpha = 0.38 - 0.47$ and a normalization, $I = 8 - 11$ keV s^{-1}cm^{-2}sr^{-1} keV^{-1} at 1 keV (Gendreau et al. 1995; Chen, Fabian & Gendreau 1997; Miyaji et al. 1998; Parmar et al. 1999). We have simulated the spectrum obtained by adding a $70 - 80$ per cent contribution to the $1 - 10$ keV flux from power-law sources with an energy index $\alpha = 0.22$ (modeling the emission from the elliptical galaxies) to the established $\lesssim 30$ per cent contribution, in the same band, from unabsorbed Seyfert-1 galaxies and QSOs (as determined from ROSAT and ASCA; e.g. Schmidt et al. 1998; Boyle et al. 1998). These latter sources have been characterized by a power-law spectrum with an intrinsic energy index, $\alpha = 0.9$, with a reflection component accounting for emission reprocessed by cold material close to the central X-ray sources (Magdziarz & Zdziarski 1995). Note that the use of a simpler power-law parameterization for the type-1 AGN, with an apparent energy index, $\alpha = 0.7$ (Turner & Pounds 1989) leads to similar results.

The simulated spectrum, as would be observed with the ASCA Solid-state Imaging Spectrometers (SIS) from a 250ks exposure (matching the total exposure time analyzed by Gendreau et al. 1995) is shown in Figure 1. The flux in the simulated spectrum matches the cosmic XRB flux observed by Gendreau et al. (1995). We do not account for the internal background in the SIS detectors, which provides an additional contribution to the total count rate detected by those authors.

Following standard X-ray analysis methods, we have fit the simulated spectrum in the $1 - 10$ keV range with a simple power-law model. We find that this model provides a good description of the simulated data (reduced $\chi^2 \sim 0.9$ for 200 degrees of freedom, after regrouping to a minimum of 20 counts per channel) and returns a best-fitting slope of $\alpha = 0.40 \pm 0.02$ or $\alpha = 0.48 \pm 0.02$ (90 per cent errors determined from monte-carlo simulations) for simulations with 20 and 30 per cent contributions to the $2 - 10$ keV flux from type-1 AGN, respectively. These results are in excellent agreement with those for the real XRB.

This simple exercise illustrates that, independently of the model used to explain the hard, power-law emission components in the elliptical galaxies, their observed $2 - 10$ keV spectra match that of the XRB in this band, once the expected contributions from QSOs and AGN are also accounted for.

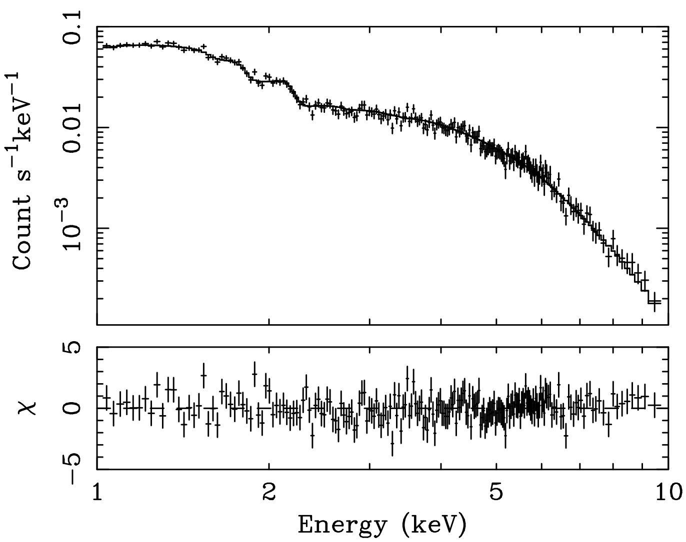

Fig. 1.— Simulated ASCA XRB spectrum. The data from all eight SIS chips have been co-added and a Galactic column density of 3×10^{20} atom cm^{-2} is assumed. A 20 per cent contribution to the $2 - 10$ keV flux from type-1 AGN is included. The upper panel shows the simulated data and best fitting power-law model, which has an energy index of 0.40 ± 0.02. The lower panel shows the residuals to the fit in units of χ.

3. BREMSSTRAHLUNG EMISSION FROM ELLIPTICAL GALAXY NUCLEI

In previous papers (DM99; Di Matteo et al. 1999b) we have shown that the broad-band spectral energy distributions for the nuclear regions of the six elliptical galaxies studied by ADF99 can be explained by low radiative efficiency accretion models (i.e. advection dominated accretion flows or ADAFs; see Narayan, Mahadevan & Quataert 1998 and references therein) in which accretion occurs from the hot, gaseous halos of the galaxies at rates comparable to their Bondi accretion rates, and in which a significant fraction of the mass, angular momentum and energy in the accretion flows is removed by winds (Blandford & Begelman 1999). Within the context of these models, the systematically hard, observed X-ray spectra can be accounted for by the energetically-dominant bremsstrahlung emission produced by such flows, with electron temperatures of $\sim 50 - 100$ keV. In this Section, we explore the implications for the XRB of this interpretation for the origin of the hard X-ray emission in elliptical galaxies.

3.1. *The XRB model*

We consider the integrated emission from unresolved sources, with hard bremsstrahlung spectra and luminosities consistent with those observed in the six nearby ellipticals studied by ADF99. We first constructed a standard coadded source spectrum by combining the results from fits to the observed spectral energy distributions for the galaxies with two-temperature ADAF models (including the effects of winds), as discussed by DM99. The contributions to the co-added spectrum from the three central cluster galaxies were down-weighted by a factor

10^2 to reflect their lower space density. The resulting co-added source spectrum has a bremsstrahlung luminosity of $8\times10^{40}\,\mathrm{erg\,s^{-1}}$ (see also Figure 2 in DM99). This standard source spectrum was then folded with the appropriate cosmological model to determine the possible, integrated contribution from such sources to the $2-60\,\mathrm{keV}$ XRB. (This model is essentially the same as that described by Di Matteo et al. (1999c) and Di Matteo & Fabian (1997), but now including the constraints on the source spectra from DM99; see Section 5 and Fig. 2 of that paper.)

We assume that the sources are distributed over a redshift range $z = z_0$ to $z = z_{\rm max}$, and write the comoving spectral emissivity from such objects as the product $j[E,z] = n(z)L_{\rm E}(z)$, where $n(z)$ is the comoving number density of X-ray sources, and $L_{\rm E}(z)$ is the specific luminosity of the individual sources. We adopt a simple prescription for the redshift evolution of the comoving emissivity, $j(E,z) = j_0(E)(1+z)^k$, where $j_0(E)$ is the model spectrum bremsstrahlung emissivity and k is the evolution parameter. The total flux from such objects is then

$$I(E) = \frac{c}{4\pi H_0} \times \int_{z_0}^{z_{\rm max}} \frac{(1+z)^{k-2}}{(1+2q_0 z)^{1/2}} j_0[E(1+z)]dz, \quad (1)$$

where q_0 is the deceleration parameter, H_0 is the Hubble constant (we use $q_0 = 0.5$ and $H_0 = 50\,\mathrm{km\,s^{-1}\ Mpc^{-1}}$) and $I(E)$ is the computed XRB intensity in units of $\mathrm{keV\,s^{-1}\ sr^{-1}\ cm^{-2}\ keV^{-1}}$ at an energy of 1 keV. For our given source spectrum and fixed values for z_0 (we assume $z_0 = 0$), $z_{\rm max}$ and k, the only free parameter in Equation 1 is the local source number density, $n(z_0)$, which we determine by normalizing $I(E)$ to the observed XRB.

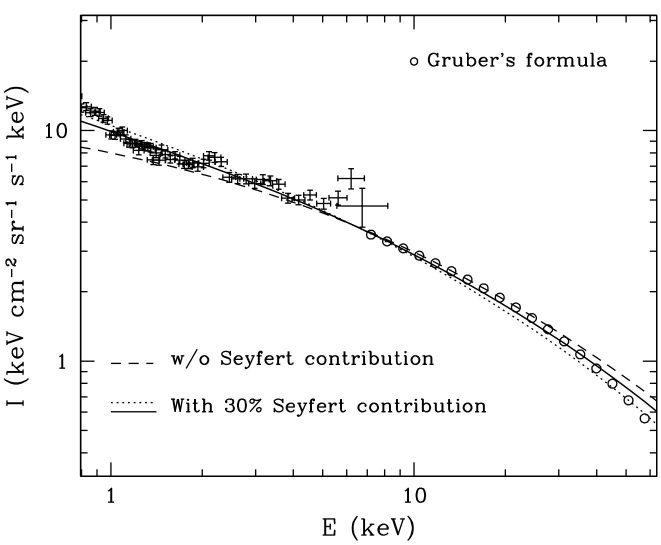

Fig. 2.— The XRB models. The dashed curve shows the result due to bremsstrahlung sources only. The solid and dotted curves include a 30 per cent contribution to the 2 keV flux from type-1 AGN. All curves assume $z_0 = 0$ and $k = 3$. The dashed and solid curves are for $z_{\rm max} = 1$. The dotted curve is for $z_{\rm max} = 1.8$. The crosses show the $1-7$ keV XRB spectrum observed with ASCA (Gendreau et al. 1995; $\alpha = 0.41\pm0.03$, $I = 8.9\pm0.4\ \mathrm{keV\,s^{-1}\ sr^{-1}\ cm^{-2}\ keV^{-1}}$ at 1 keV). The positive residual at 6.4 keV is an instrumental emission line). The circles show the Marshall et al. (1980) result from HEAO A2 data in the $3-60$ keV band (a power-law spectrum with an energy index, $\alpha = 0.4$, and an exponential rollover at ~ 30 keV; see also Gruber 1992).

The XRB spectra predicted by a series of 'best fit' models are shown in Figure 2. The dashed line shows the result due only to bremsstrahlung sources. The solid line shows the improved result when we include a 30 per cent contribution to the 2 keV flux from unabsorbed AGN (corresponding to a ~ 20 contribution to the $2-10$ keVflux), characterized by a canonical power-law spectrum with an energy index, $\alpha = 0.7$. (Both curves assume $z_{\rm max} = 1.0$ and $k = 3$.) In this case, the normalization of the XRB requires a local comoving number density of bremsstrahlung sources, $n(z_0 = 0) \sim 2\times10^{-3}\,\mathrm{Mpc^{-3}}$. The dotted line in Figure 2 shows the result for $z_{\rm max} = 1.8$ (other parameters the same) in which case $n(z_0 = 0) = 8\times10^{-4}\,\mathrm{Mpc^{-3}}$ (the most distant sources contribute most to the total model flux). These values for the comoving number density of emitting sources are in good agreement with the observed number density of bright, early-type galaxies in the nearby Universe ($n \sim 10^{-3}\,\mathrm{Mpc^{-3}}$ e.g., Marinoni et al. 1999; Heyl et al. 1997).

4. DISCUSSION

We have shown that our model provides a good match to the observed XRB, with a required number density of emitting sources in good agreement with the observed number density of early-type galaxies in the nearby Universe (for $z_{\rm max} \gtrsim 1$ and $k \sim 3$). The requirement for most/all early-type galaxies to have hard X-ray spectra and luminosities consistent with the objects studied by ADF99 may be relaxed once more realistic models for the XRB are considered, including a fractional contribution from heavily absorbed Seyfert-2 nuclei (e.g. Gilli et al. 1999). This will then allow for a broader range of luminosities and/or a lower number density for the bremsstrahlung sources. (In this case the relative contribution from these sources to the $2-10$ keV XRB intensity will also be rescaled to < 70 per cent.) The required comoving number density of bremsstrahlung sources is also decreased as $z_{\rm max}$ is increased towards $z_{\rm max} \sim 2$.

It is important to note that our sources may also contribute to the hard number counts detected at faint X-ray fluxes by ASCA and BeppoSAX (e.g. Ueda et al. 1998; Fiore et al. 1999). Detailed synthesis models for the XRB, which simulate the integrated emission from AGN with a range of absorbing column densities, have revealed the need for additional hard spectrum sources to explain the observed number counts (e.g., Gilli et al. 1999). The $2-10$ and $5-10$ keV fluxes associated with the power-law sources detected in the nearby ellipticals studied by ADF99 range from $0.6-8.7$ and $0.3-5.0\times10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, respectively. Within the context of our model, a significant fraction of the hard number counts detected at fluxes, $F_{\rm X,2-10} \lesssim$ a few $10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$; may then arise from sources at low redshift. We note that models postulating the existence of an as yet unobserved population of heavily obscured black holes at redshift, $z \sim 2$, also predict X-ray fluxes too faint to account for the observed hard counts (Fabian 1999).

The value of $z_{\rm max}$ in our model is constrained by the effective temperature of the bremsstrahlung emission in

the coadded source spectra: the coadded spectrum must be redshifted to fit the 30 keV rollover observed in the XRB. We note that the high-energy ($\gtrsim 50\,$keV) spectrum predicted by our model is not firmly constrained. The presence of winds/outflows associated with low radiative efficiency accretion flows around supermassive black holes inevitably causes the X-ray spectra of such flows to be dominated by bremsstrahlung emission. (Inverse Compton emission is heavily suppressed in the presence of outflows for any range of $\dot{m}$; this, with $\dot{m} \sim \dot{m}_{\rm crit}$ for the component sources, allows for higher individual bremsstrahlung source luminosities than considered in the earlier work of Di Matteo & Fabian.) However, the wind characterization currently employed in the accretion models is very basic and the spectra produced cannot be used to perform reliable statistical fits to the data. In particular, the presence of an outflow will significantly affect the density and temperature profiles in the central regions of an ADAF (c.f. DM99; Quataert & Narayan 1999), where the higher energy ($h\nu \gtrsim kT$) emission originates (although the emission in the $2-10\,$keV band, where the models provide a good match to the power-law components observed in nearby ellipticals, is virtually unaffected). Due to these uncertainties the value of $z_{\rm max}$ cannot be tightly constrained.

The black holes at the centers of nearby elliptical galaxies have masses consistent with being the remnants of an earlier quasar phase. If, as our work may suggest, these systems accrete via low-radiative efficiency accretion flows, then a fraction of the hard XRB could be produced after the main quasar phase in galaxies and be associated with a change in the dominant accretion mechanism in their nuclei (see also Di Matteo & Fabian 1997). It is interesting, in this context, that studies with the Hubble Space Telescope have shown the underlying hosts of essentially all classes of QSOs appear to be massive, elliptical galaxies (McLure et al. 1999).

We stress that our analysis is not intended to explore the full range of parameter space available to either the accretion flow or XRB models, or to provide detailed, quantitative results. At present, the theoretical and observational uncertainties involved in such calculations are too large to merit such work. The observational constraints will, however, be significantly improved in the near future with data from the Chandra Observatory, XMM and ASTRO-E

5. CONCLUSIONS

We have examined the potential importance of the hard, power-law emission components detected in the X-ray spectra of nearby ellipticals for the origin of the hard XRB. In previous papers (ADF99 and DM99) we have shown that these components are likely to be associated with accretion onto the central, supermassive black holes in the galaxies. The emission spectra from these sources can be well-explained by bremsstrahlung models, with typical temperatures of $50-100\,$keV, resulting from low radiative-efficiency accretion flows with strong winds. In this paper we have shown that the application of such emission models to a plausible redshift distribution of sources, with individual source luminosities in agreement with the ASCA results for nearby ellipticals, can account for a significant fraction of the XRB in the $1-60\,$keV range, with an implied number density of sources in good agreement with the observed local number density of early-type galaxies. We have argued that the emission from these sources may also contribute to the hard number counts detected at faint X-ray fluxes with ASCA and BeppoSAX.

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REFERENCES

Allen, S. W., Di Matteo, T., Fabian A. C. 1999, MNRAS, in press (ADF99)
Blandford, R. D., Begelman M. C. 1999, MNRAS, 303, L1
Boyle, B. J., Georgantopoulos, I., Blair, A. J., Steward, G. C., Griffiths, R.,E., Shanks, T., Gunn, K. F., Almaini O. 1998, MNRAS, 296, 1
Chen, L.-W., Fabian A. C., Gendreau, K. C., 1997, MNRAS, 285, 449
Comastri, A., Setti, G., Zamorani, G. 1995, A&A, 296, 1
Di Matteo, T., Fabian, A. C. 1997, MNRAS, 286, 393
Di Matteo, T., Esin, A., Fabian, A.C., Narayan R., 1999c, MNRAS, 305, L1
Di Matteo, T., Fabian, A. C., Rees, M. J., Carilli, C. L., Ivison, R. J. 1999b, MNRAS, 305, 492
Di Matteo, T., Quataert, E., Allen, S. W., Narayan, R., Fabian, A. C., 1999a, MNRAS, in press (DM99)
Fabian, A. C., 1999, MNRAS, in press
Fabian, A. C., Rees M. J. 1995, MNRAS, 277, L55
Gendreau, K. C., et al. 1995, PASJ, 47, L5
Gilli, R., Risaliti, G., Salvati, M. 1999, A&A, in press
Giommi P., et al. 1998, Nucl.Phys B, 69/1-3, 591
Gruber, D. E., 1992, in Barcons X., Fabian A. C., eds, Proc. of The X-ray Background, Cambridge Univ. Press, Cambridge, p.44
Fiore, F., La Franca, F., Giommi, P., Elvis, M., Matt, G., Comastri, A., Molendi, S., Gioia, I. 1999, MNRAS, in press [astro-ph/9903447]
Hasinger, G., Burg, R., Giacconi, R., Schmidt, M., Trümper, J., Zamorani, G. 1998, A&A, 329, 482
Heyl, J., Colless, M., Ellis, R.S., Broadhurst, T., 1997, MNRAS, 285, 613
McLure, R. J., Dunlop, J. S., Kukula, M. J., Baum, S. A., O'Dea C. P., Hughes D. H., 1999, ApJ, submitted, (astro-ph/9809030)
Magdziarz, P., Zdziarski, A.A., 1995, MNRAS, 273, 837
Marshall, F. E., Boldt, E. A., Holt, S. S, Miller, R. B., Mushotzky, R. F., Rose, L. A., Rothschild, R. E., Serlemitsos, P. J., 1980, ApJ, 235, 4
Magorrian J. et al. 1998, AJ, 115, 2285
Marinoni, C., Monaco, P., Giuricin, G., Costantini, B. 1999, preprint (astro-ph/9903394)
Miyaji, T., Hasinger G., Schmidt M., 1999, Adv. Space Res., in press
Miyaji, T., Ishisaki, Y., Ogasaka, Y., Ueda Y., Freyberg, M.J., Hasigner, G., Tanaka, Y., 1998, A&A, 334, L13
Narayan, R., Mahadevan, R., Quataert, E. 1998, Theory of Black Hole Accretion Disks, edited by Marek A. Abramowicz, Gunnlaugur Bjornsson, and James E. Pringle. Cambridge University Press, p.148
Parmar, A.N., Guainazzi, M., Oosterbroek, T., Orr, A., Favata, F., Lumb, D., Malizia, A., 1999, A&A, 611
Quataert, E., Narayan, R. 1999, ApJ, in press
Schmidt, M. et al. 1998, A&A, 329, 495
Setti G., Woltjer L., 1989, A&A, 224, L21
Turner, T. J., Pounds. K. A. 1989, MNRAS, 240, 833
Ueda et al. 1998, Nature, 391, 866